KAWASAKI STEEL TECHNICAL REPORT
No.18 (May 1988)

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The body can be viewed from the next page.

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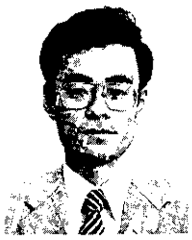

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Synopsis:

Hot rolled steel sheet with extra-low carbon content which exhibits excellent formability has been newly developed in Kawasaki Steel. Chemical composition of this steel is specially controlled, that is to say, sulfur content is 0.003 wt% or less and titanium is added so that the effective Ti/C atomic ratio will come to more than 1.0. In the hot rolling process, this steel is coiled at a temperature lower than 600°C. The characteristics of this steel are as follows:

(1) Total elongation is 55% or higher (3.2 mm thick).
(2) Planar anisotropy is minimal in spite of Ti-addition.
(3) This steel exhibits a higher resistance to cold-work brittleness due to the control of both residual solute carbon content and fine grain sizes.

1 Introduction

To meet the increasingly stringent requirements for formability of steel sheets, Kawasaki Steel has previously developed the extradeep-drawing cold-rolled steel sheets **KTUX** and **CHRX**[1,2], and the hot-rolled B-bearing low-carbon steel sheet **KFN1** and hot-rolled B-bearing ultra-low-carbon steel sheet **KFN2**[3]. Due to the well known difficulty in improving $\bar{r}$-value (Lankford value) of hot-rolled steel sheets by controlling their recrystallization texture, cold-rolled steel sheets have often been preferred for deep-drawing parts in the thickness range from 1.6 to 3.2 mm where hot- and cold-rolled steel sheets are used competitively.

In recent years, hot-rolled steel sheets have often been required to match the excellent formability of deep-drawing-quality cold-rolled steel sheets (SPCE). In the thickness range over 3.2 mm, in which the production of cold-rolled steel sheets is difficult, better formability than that of KFN1 and KFN2 has been demanded in many cases.

The maximum $\bar{r}$-value of hot-rolled steel sheets is 1.0, and it might be thought that hot-rolled steel sheets must possess better ductility than cold-rolled steel sheets if the same formability as that of cold-rolled steel sheets is to be obtained. With respect to the composition of hot-rolled steel sheets with excellent formability, various techniques, as enumerated below, have been proposed:

(1) Decreasing the Al and N contents[4]
(2) Decreasing the C content to ultralow levels[5]
(3) Adding B to low-carbon or ultralow-carbon steels[3]
(4) Adding minute amounts of Ti and Nb to ultralow-carbon steels[5]

However, ductility remains somewhat insufficient in (1) to (3) and the orange peel due to grain coarsening tends to occur in (1) and (2). In (4), the strength of grain boundaries decreases due to the lack of solute C and N caused by Ti and Nb addition; this results in cold-work

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brittleness after deep drawing. In (4), an improvement in resistance to cold-work brittleness can be expected when Ti and Nb contents are lowered to below the equivalent contents of C and N. In this case, however, it is difficult to adjust compositions, and the same problems as with (2) occur if Ti and Nb contents are low.

To solve these problems, Kawasaki Steel has recently developed a hot-rolled steel sheet with excellent formability, **KFN3**. In KFN3, high ductility and grain refinement are achieved by controlling hot rolling conditions using a Ti-bearing ultralow-carbon steel as the base steel. The formation of residual solute carbon is stably promoted by decreasing the S content to 0.003% or less, which increases the strength of grain boundaries, thereby improving cold-work brittleness.

This paper describes results of fundamental experiments carried out preparatory to the development of the extradeep-drawing hot-rolled steel sheet KFN3, and describes the mechanical properties of this steel sheet.

2 Required Properties of Hot-Rolled Steel Sheets for Severe Forming

Hot-rolled steel sheets for severe forming must possess the following characteristics:

(1) Higher ductility than that of cold-rolled steel sheets
(2) Small planar anisotropy—one of the important features of hot-rolled steel sheets
(3) High resistance to cold-work brittleness after deep drawing

High ductility of 55% or more was aimed at in KFN3, considering that the total elongation (El) of cold-rolled steel sheets (SPCE, 3.2 mm$t$) ranges from about 52% to 55% and that the $\bar{r}$-value of hot-rolled steel sheets is 1.0 or less.

There are many applications where the small planar anisotropy of hot-rolled steel sheets is required. Compressor vessels for air conditioners are a typical example. In order to meet rigorous requirements for roundness and thickness accuracy, it is necessary to minimize planar anisotropy. Smaller planar anisotropy than that of cold-rolled steel sheets is required and in this case was obtained by conducting hot rolling at finish rolling temperatures of Ar_3 or above. Steel compositions was also examined in consideration of isotropy.

Cold-work brittleness (to be described in detail below) is the phenomenon in which brittle cracks are initiated when impact is applied at low temperature to deep-drawn parts such as pressure vessels and compressor vessels. In this connection, it is necessary to take measures to prevent the intergranular fracture peculiar to ultralow-carbon steels.

In developing KFN3, an ultralow-carbon steel was used as the base steel to meet requirements for high ductility. When an ultralow-carbon steel is used, and neither Nb nor Ti is added, high coiling temperatures of 640°C or above are necessary to stabilize the solute N in the steel in the form of AlN. In addition, deterioration in descalability and changes in mechanical properties in the longitudinal direction often occur. Furthermore, room temperature aging property may deteriorate because the greater portion of the carbon exists in solute state. However, the presence of solute C suppresses the boundary segregation of P and increases the strength of grain boundaries, thereby improving resistance to cold-work brittleness.

On the other hand, with an ultralow-carbon steel to which Nb and Ti are added, grain refinement and improved room temperature aging property can be expected, with high ductility maintained. However, Nb and Ti retard the recrystallization of the γ-phase during hot rolling and may cause the formation of a texture unfavorable to planar isotropy. In addition, the decreased amounts of solute C and N cause deterioration in cold-work brittleness resistance.

However, if an appropriate combination of composition and hot rolling conditions is selected, it is possible to produce steel sheets excellent in both planar isotropy and cold-work brittleness resistance, as shown by the present development project.

3 Examination of Composition and Hot Rolling Conditions

Steels of the chemical compositions shown in **Table 1** were melted using a commercial production mill and were continuously cast into slabs after RH degassing. Hot rolling was conducted at a slab reheating temperature (ST) of 1 250°C, finish rolling temperatures (FT) of 900 to 910°C ($\geq Ar_3$) and coiling temperatures (CT) of 540 and 675 to 680°C. The thickness was 3.5 mm. The mechanical properties are shown in **Table 2**. The values of $\overline{El}$ and $\bar{r}$ are average values of specimens taken longitudinal to the rolling direction, transverse to the rolling direction and at an angle of 45° to the rolling direction.

Table 1 Chemical composition and coiling temperature of steels* used

	Chemical composition (wt. %)								CT (°C)
	C	Mn	P	S	Al	N	Ti	Nb	
TH	0.0015	0.09	0.011	0.002	0.028	0.0022	0.028	—	675
TL	〃	〃	〃	〃	〃	〃	〃	—	540
TNH	0.0025	0.10	0.012	0.004	0.028	0.0028	0.024	0.007	685
TNL	〃	〃	〃	〃	〃	〃	〃	〃	540
NH	0.0021	0.11	0.010	0.005	0.031	0.0024	—	0.019	680

* Thickness: 3.5 mm

Table 2 Effects of Ti and Nb addition and coiling temperature on mechanical properties

Steel	YS*1 (kgf/mm²)	TS*1 (kgf/mm²)	$\bar{El}$*2 (%)	$\bar{r}$*2	ΔEl*2 (%)	Δr*2	AI*3 (kgf/mm²)
TH	16.8	28.7	59.6	0.90	−3.8	−0.37	0.0
TL	17.1	29.4	56.7	0.89	−0.5	−0.20	2.8
TNH	17.0	28.8	57.0	0.92	−1.2	−0.15	0.2
TNL	19.3	29.9	54.6	0.92	−0.7	−0.15	2.9
NH	19.5	32.1	53.4	0.79	−1.4	−0.18	0.0

*1 YS and TS were tested in the rolling direction.

*2 The average values, El and $\bar{r}$, were calculated by Eq. (1) and the planar anisotropy values, ΔEl and Δr, by Eq. (2).

$$\bar{x}=(x_0+x_{90}+2x_{45})/4 \quad \cdots\cdots (1)$$

$$\Delta x=(x_0+x_{90}-2x_{45})/2 \quad \cdots\cdots (2)$$

(Suffix: angle from rolling direction)

*3 AI is the increase in yield strength after 7.5% pre-strain and aging treatment at 100°C for 30 min.

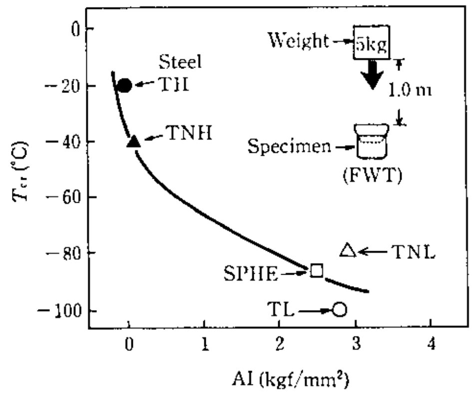


Fig. 1 Effect of AI on cold-work brittleness transition temperature (Cups, drawn at drawing ratio of 2.0, were subjected to the drop weight test(FWT) at various temperature shown in this figure.)

ΔE1 and Δr denote amounts of planar anisotropy. The aging index (AI) gives a measure of the solute C and N contents and indicates an increase in the yield point after 7.5% pre-straining and accelerated aging at 100°C for 30 min.

It is apparent that the ductility of the Nb bearing steel (NH) is low even after high-temperature coiling. Ductility is also low in the Ti and Nb-bearing steel (TNL) coiled at low temperature. Furthermore, it was found that the planar anisotropy of the Ti-bearing steel (TH) coiled at high temperature was large. AI is high in Ti-bearing steels (TL and TNL) coiled at low temperatures. It is thought that in these steels, N precipitates as TiN during slab reheating. Therefore, an AI of 2.5 to 3 kgf/mm² resulting from the presence of residual solute C, corresponds to 2 to 5 ppm of solute C, as measured by the internal friction method.[6] According to a report made by Konishi et al.[7], the existence of very low solute C contents of 1 ppm or less which cannot be detected by the internal friction method, greatly increases the strength at grain boundaries. Therefore, a study was made of the resistance to cold-work brittleness of the Ti-bearing steel and Ti- and Nb-bearing steel. In this investigation, a cup specimen drawn at a drawing ratio of 2.0 using a 50 mmϕ cylindrical punch was held at a predetermined temperature, after which a 5 kg weight was dropped from a height of 1.0 m onto the specimen into which a conical shaped weight with a head angle of 60° had been pushed. The temperature at which brittle crack was initiated was regarded as the embrittlement temperature (T_{cr}).

The relationship between the brittle-crack initiation temperature and the aging index is shown in **Fig. 1**. The embrittlement temperatures of steels TL and TNL, with high AI-values, are by far lower than those of steel TNH with AI ≒ 0 kgf/mm². A value obtained for steel SPHE is also plotted in the figure. It is apparent that ultralow-

a: CT=540°C

b: CT=680°C

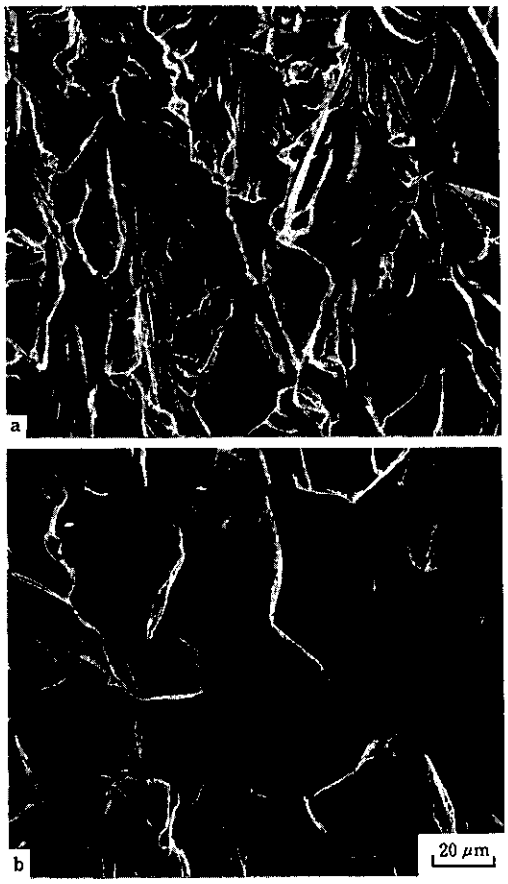


Photo 1 Scanning electromicrographs of brittle fracture showing the effect of coiling temperature

carbon steel with AI of 2.5 to 3 kgf/mm^2 has a resistance to cold-work brittleness equal to or better than that of the low-carbon steel SPHE. In steel TH, with large planar anisotropy, earing of about 1.5 to 1.8 mm occurred after deep drawing while other steels showed earing of 0.6 to 0.8 mm. This suggests the possibility that the impact energy in the drop weight test may have affected the ends of the specimen nonuniformly, and this is a distinct difference between TH and steels with high AI-values. Fracture surfaces of steels TL and TH at brittle-fracture initiation temperatures are shown in **Photo 1.** The steel coiled at high temperature (steel TH, $T_{cr} = -20°C$) shows grain boundary fracture caused by the virtual absence of solute C. On the other hand, the steel coiled at low temperature (steel TL, $T_{cr} = -100°C$) shows cleavage fracture, suggesting that the residual solute carbon effectively increase the strength of grain boundaries. Incidentally, if the AI-value increases further ($\geqq 4$ kgf/mm^2), an increase in the yield point and a deterioration in ductility may occur due to the progress of strain aging at room temperature. It seems, however, that these phenomena pose no problems from a practical standpoint because the AI-values of the steels used in this experiment were of low levels, which are regarded as non-aging.

The above series of tests showed that all the requirements for steel sheets with excellent formability can be met by Ti-bearing ultralow-carbon steel sheet produced at low coiling temperature (the steel TL).

4 Investigation of AI, Cold-Work Brittleness Resistance, and Planar Anisotropy

4.1 Effect of S Content on AI[8)]

It is known that Ti forms nitrides and sulfides at high temperatures such as slab reheating temperatures. Furthermore, Ti reacts with C to form carbides at relatively low temperatures depending on the effective Ti content ($Ti^* = Ti - Ti_{asTiN} - Ti_{asTiS}$). For example, in the Ti-bearing steels shown in Table 1, the temperature at which TiC would be completely dissolved is estimated at 700°C when calculated using the equilibrium solubility product in the γ-phase as proposed by Irvine et al.[9)] No definite conclusion can be drawn because there is no reliable solubility product of TiC in the α-phase. It appears likely, however, that Ti carbides are formed at very low temperatures.

In Ti-bearing ultralow-carbon steel sheets coiled at low temperature and meeting the requirements for steel sheets for severe forming, the atomic ratio of effective Ti to C is very high at 2.9, and the Ti content is excessive relative to the amount of C. In these steels, therefore, it has been considered that there is scarcely any residual solute C. In the present experiment, however, AI = 2.5 to 3.0 kgf/mm^2 indicating that residual solute C amounted to 2 to 5 ppm. Since even Ti- and Nb-bearing steel sheets coiled at a low temperature show almost the same AI-values as those mentioned above, this may be caused by the fact that the precipitation temperature of Ti carbides in ultraclean steels with very low C and N contents is much lower than that of conventional interstitial-free (IF) steels. However, the existence of residual solute C at effective Ti/C atomic ratios much higher than 1.0 cannot be explained on this assumption.

Therefore, the effect of S content on AI was investigated, on the assumption that very low S contents of the tested steels was the cause of these results with regard to AI and solute C.

Titanium-bearing ultralow-carbon steels with different S and Ti contents, which are shown in **Table 3**, were experimentally vacuum-melted and used as test materials. Each steel's 100-kg ingots were heated at 1 250°C for 30 min and slabbed to a thickness of 30 mm. These slabs reheated to 1 000°C, a temperature below the dissolving point of TiN and TiS, are hot rolled to a thickness of 3.5 mm at finish rolling temperatures of 880°C or more, and then air cooled.

The AI-values of these hot-rolled steel sheets are shown in **Fig. 2**. When the AI-values are rearranged so

Table 3 Chemical compositions of vacuum-melted steels used (wt%)

(wt %)

Steel	C	Mn	P	S	Al	N	Ti	Ti*/C
A1	0.0034	0.11	0.009	0.0013	0.047	0.0008	0.013	0.6
A2	0.0026	0.10	0.010	0.0008	0.048	0.0009	0.023	1.8
A3	0.0034	0.10	0.009	0.0032	0.054	0.0008	0.017	0.7
A4	0.0030	0.11	0.009	0.0032	0.053	0.0009	0.028	1.7
A5	0.0023	0.10	0.009	0.0087	0.049	0.0008	0.023	0.8
A6	0.0025	0.11	0.009	0.0086	0.052	0.0008	0.033	1.7

Note (1) Ti*/C: atomic ratio

$$Ti^* = Ti - \left(\frac{48}{14}N + \frac{48}{32}S\right)$$

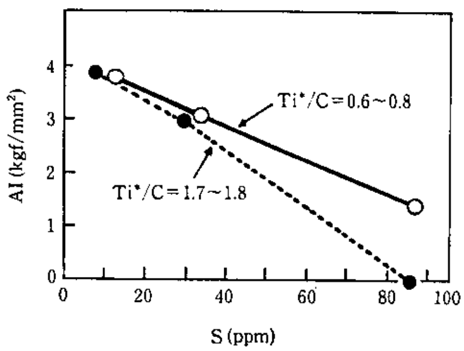


Fig. 2 Effects of S content and Ti*/C (atomic ratio) on AI

that the atomic ratios of effective Ti to C (Ti*/C) are almost equal, then AI ≒ 0 kgf/mm², if the S content is of a conventional level (0.008%) and Ti*/C > 1.0. This value is in agreement with results obtained to date. On the other hand, when the S content is 0.0032% or less, AI = 3 to 4 kgf/mm², suggesting that the amount of residual solute C increases.

It is supposed that S content has some effect on the carbide precipitation behavior of Ti-bearing steels, a supposition now being examined. It is thought that the precipitation of Ti carbides at low temperatures is for some reason retarded by a decrease in the S content, since AI ≒ 0 kgf/mm² in steel sheets coiled at a high temperatures, including Ti-bearing steels.

4.2 Resistance of KFN3 to Cold-Work Brittleness

4.2.1 Effects of AI and grain size on resistance to cold-work brittleness

KFN3 is produced by coiling a Ti-bearing ultalow-carbon steel strip with a S content of 0.003% or less at a temperature of 600°C or less. As mentioned above, resistance to cold-work brittleness is improved when the strength of grain boundaries is increased by promoting residual solute C. When resistance to cold-work brittleness is good and only cleavage fracture occurs, as with KFN3, it was predicted that brittleness behavior would be greatly affected by grain size. To test this, a 2.6-mm thick KFN3 steel sheet manufactured by a commercial production equipment (CT = 540°C) was experimentally reheated, held at a specified temperature (T_h) for 5 min, and air cooled, thereby changing the grain size and AI. The embrittlement temperature (T_{cr}) was measured by the method described above. Results of this investigation are shown in **Fig. 3**. When $T_h \geqq$ 750°C, AI decreases; when $T_h \geqq$ 850°C, grain coarsening occurs. Thus, the embrittlement temperature is higher than when T_h = 540°C (in the as-rolled condition). Grain boundary fracture occurred when $T_h \geqq$ 750°C, and cleavage fracture occurred when $T_h \leqq$ 650°C.

The relationship between the grain size and embrittlement temperature of the KNF3 steel sheet produced by the commercial production mill is shown in **Fig. 4**. The embrittlement temperature corresponds well with grain size, rising with increasing grain size. The figure also shows the effect of cooling patterns from the completion of finish rolling to coiling. In a cooling pattern with rapid cooling in the latter half of the cooling process, resistance to cold-work brittleness is inferior due to an increase in grain size. Incidentally, the data shown in the figure was obtained at coiling temperatures of 500 to 600°C and AI of 2.5 to 3.2 kgf/mm², and AI changed little even when the cooling pattern was changed.

From the foregoing, it seems important to control grain size in addition to promoting residual solute carbon in order to improve the resistance to cold-work brittleness of KFN3. In this steel, grain refining is accomplished without deterioration in ductility by Ti addition with Ti*/C > 1.0 and cooling pattern control as well as low-temperature coiling (CT ≤ 600°C) adopted.

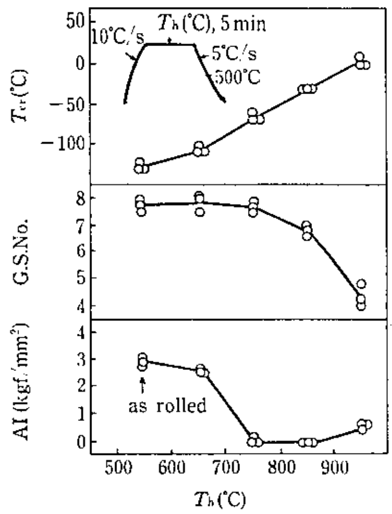


Fig. 3 Dependence of T_{cr}, grain size number (G.S.No.) and AI on soaking temperature T_h prior to drawing

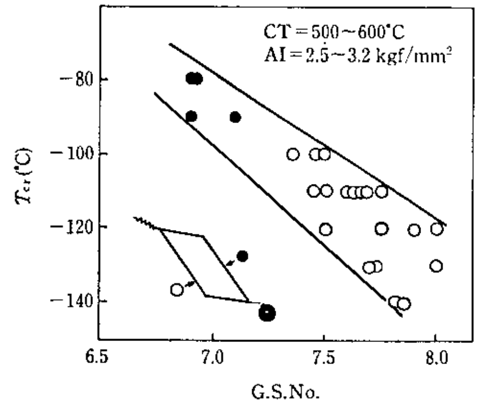


Fig. 4 Effects of grain size and cooling pattern after finish rolling (Open mark ○ stands for rapid cooling at a higher temperature range and slow cooling at a lower temperature range on the run-out table, and solid mark ● is for vice versa.)

4.2.2 Effect of strain aging on resistance to cold-work brittleness

In KFN3, the strength of grain boundaries is increased by promoting residual solute C. The existence of solute C causes an increase in matrix strength due to

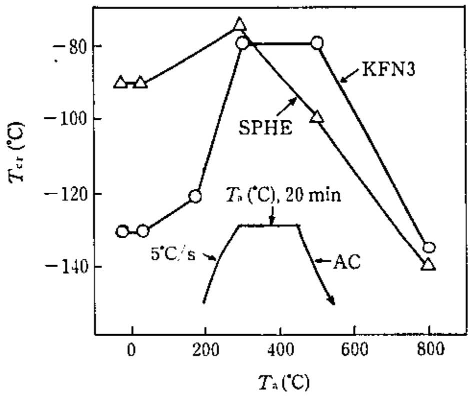


Fig. 5 Effect of heating temperature T_a after cup forming on T_{cr}

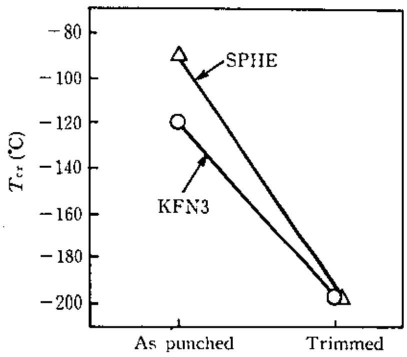


Fig. 6 Effect of finishing condition of cup edge on T_{cr}

strain aging resulting from heat treatment, such as baking in the painting process, which follows press forming. Therefore, to investigate changes in embrittlement temperature, a KFN3 steel sheet was deep drawn at a drawing ratio of 2.0 and subjected to heat treatment involving rapid heating (5°C/s) in a temperature range of −20°C (storage in a freezing chamber) to 800°C and air cooling after holding for 20 min. The steel sheet was held at −20°C to prevent strain aging in the period from the completion of forming to the start of heat treatment. A comparison of changes in the embrittlement temperatures of KFN3 and SPHE is shown in **Fig. 5**. The KFN3 steel sheet shows only a slight increase in embrittlement temperature even if subjected to heat treatment at 170°C, a temperature equivalent to baking in the painting process. Because the fracture surface was of the cleavage type in this case, it is considered that the strength of grain boundaries decreased only slightly, even with heat treatment equivalent to baking in the painting process, and that resistance to cleavage fracture decreased slightly due to an increase in matrix strength. When the reheating temperature is in the range of 300 to 500°C, the embrittlement temperature is 40 to 50°C higher than holding at room temperature or −20°C. Because the same tendency was observed with SPHE, it seems likely that in this temperature range the progress of strain aging due to solute C (in SPHE, solute C is redissolved during heating) occurs preferentially to the effect of stress-relieving annealing. At a heating temperature of 800°C, the embrittlement temperature decreases again, which corresponds with the recrystallization.

4.2.3 Effect of specimen edges on resistance to cold-work brittleness

Because the earing height of KFN3 (steel sheet coiled at a low temperature) and SPHE after deep drawing was small at 0.6 to 0.8 mm, the embrittlement test in this report was carried out on a specimen with a punched edge. When the embrittlement test is conducted using a drop weight, the edge is a brittle-fracture initiation point. Accordingly, edge properties are considered as a factor in the evaluation of resistance to cold-work brittleness. For this reason, a comparison of the embrittlement temperature was made between deep drawn cup specimens obtained by drawing a sheet (2.6 mm$t$) with a punch 50 mm in diameter (average height: 38 to 39 mm) and the edges of which were subjected to precision cut with a microcutter to a height of 35 mm after drawing. Results of this comparison are shown in **Fig. 6**.

A brittle crack is initiated at −196°C in both KFN3 and SPHE by removing the punched edge. The embrittlement temperature decreased by about 70°C in KFN3 and by about 100°C in SPHE. An area which provided a fracture surface as punched edge was cut off parallel to the sheet surface and inspected, as shown in **Photo 2**. SPHE shows larger macroscopic irregularities resulting from the shrinkage deformation of flange during deep drawing. Furthermore, a large number of microcracks were observed in SPHE, though hardly any were found in KFN3. Although the existence of microcracks has already been reported[10], they were not observed in KFN3 in the present case. The reason microcracks are observed in SPHE but not in KFN3 is not clear. A possible explanation for this phenomenon follows. Since SPHE is a low-carbon steel, relatively coarse grained pearlite or cementite exists, and microcracks are apt to form during punching and drawing. It is considered, in any case, that the presence or absence of these microcracks is one possible reason the effect of the edge on the embrittlement temperature was different in SPHE and KFN3.

In applying the above results to actual pressed parts, it can be said that it is desirable to conduct an embrittlement test on specimens with edges remaining when working portions which may develop brittle cracking, for example, when conducting piercing after deep drawing or burring of pierced holes. On the other hand, it is advisable to conduct the test on specimens from which

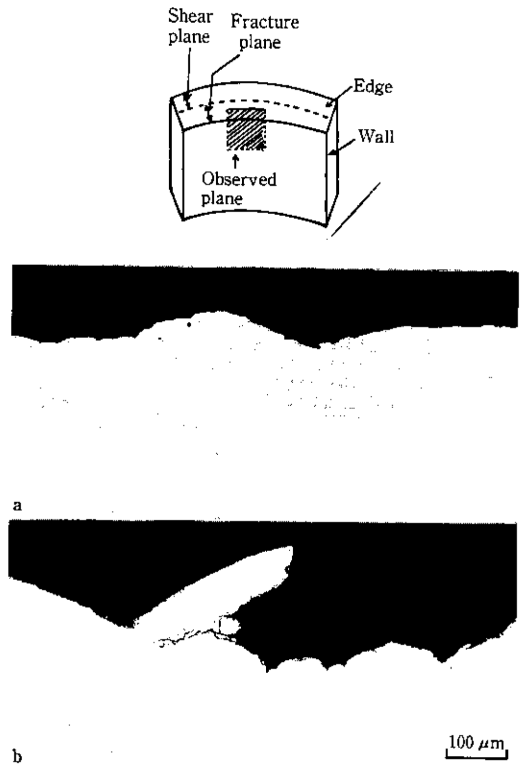


Photo 2 Comparison of roughness and small crack initiation at the edge of deep-drawn cups between (a) KFN3 and (b) SPHE

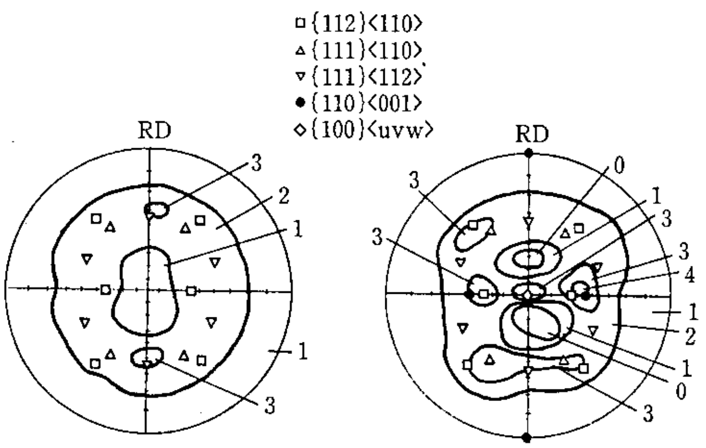
the edges have been removed when the edge would have little effect on a portion which may develop brittle cracking, for example, when the edge is removed or when eliminating the effect of edges by welding.

In actual pressed parts, further complex factors, such as degree of forming (drawing ratio), degree of impact and working temperature are involved, and it is difficult to evaluate the effect of the edge as an absolute value as can be done in the tensile test. Nevertheless, the authors are continuing their examination of these problems.

4.3 Planar Anisotropy of KFN3

Unlike cold-rolled steel sheets, it is impossible to develop {111} texture parallel to the sheet surface in hot-rolled steel sheets. Ordinarily, rolling is completed at the Ar_3 point or above to obtain random orientation. On the other hand, it is reported[11] that in steels to which Ti, Nb, B, etc., are added, the recrystallization of the γ-phase is suppressed during hot rolling and specific orientations such as {111}[112] and {112}[110] develop, thus showing unusual planar anisotropy.

Figure 7 shows (200) pole figures in the position corresponding to 1/4 thickness of a KFN3 steel sheets coiled at low (CT = 540°C) and at high temperatures (CT = 680°C). It is apparent that a random orientation and small planar anisotropy can be achieved if rolling is completed at Ar_3 or above and low-temperature coiling is conducted. On the other hand, a relatively intense cumulative tendency is observed in {111}∥ND, {100}∥ND and {110}[001] in the KFN3 steel sheet coiled at high temperature. Grain growth at a specific orientation during the cooling between rolling and coiling and selective grain growth at a specific orientation during holding at a high temperature after coiling are possible explanations of this phenomenon. Concerning the former, however, no change in planar anisotropy was observed when grains were caused to grow by adopting the cooling pattern with rapid cooling in the latter half of the cooling process shown in Fig. 4, and therefore, the latter is considered the main cause. The relationship between Δr and coiling temperature is



(a) CT=540°C (b) CT=680°C

Fig. 7 Effect of coiling temperature on (200) pole figure

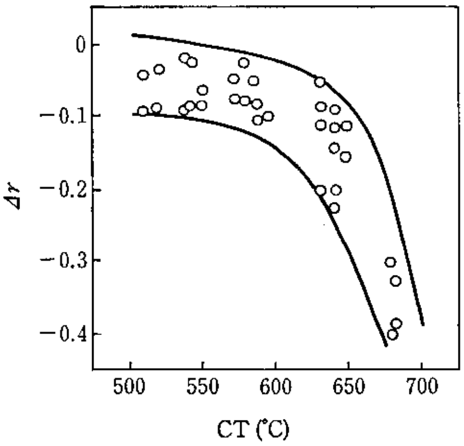


Fig. 8 Effect of coiling temperature(CT) on planar anisotropy of r-value(Δr)

shown in **Fig. 8**. Planar anisotropy was small when CT $\leqq$ 600°C.

KFN3 steel sheets have the same small planar anisotropy as SPHE steel sheets if finish rolling is completed at Ar_3 or above and low-temperature coiling is conducted so that grain growth does not occur.

5 Comparison of Mechanical Properties of KFN3 and Conventional Steels

Figures 9 and **10** show a comparison of mechanical properties and characteristic values of KFN3 and other hot-rolled steel sheets, i.e., SPHE (low-carbon Al-killed steel), KFN1 (B-bearing low-carbon Al-killed steel), and KFN2 (B-bearing ultralow-carbon Al-killed steel). KFN1 and KFN2 show somewhat larger planar anisotropy than KFN3 and SPHE and somewhat higher embrittlement temperatures. KFN3 has excellent ductility of 55% or more at a thickness of 3.2 mm. KFN3 shows the highest limiting drawing ratio (LDR) of all the hot-rolled steel sheets, although its value is inferior to those of the cold-rolled steel sheet SPCE which range from 2.15 to 2.20. If the fact that an SPCE steel sheet of the same thickness has an El of 52 to 55% is considered, it would appear that KFN3 has the same press formability as SPCE. In addition, KFN3 is good both in stretch-flangeability (bore expanding ratio) and stretchability (bulge height).

As mentioned above, KFN3 was developed based on the Kawasaki Steel's techniques for producing ultraclean steels. Its excellent features make it suitable for applications including extradeep-drawn parts, such as compressor vessels and automotive underbody parts, which are subjected to severe forming. Incidentally, KFN3 has the same phosphatability as SPHE. It has been ascertained that the deterioration of its mechanical properties is slight when it is subjected to heat treatment conditions equivalent to those in hot-dip galvanizing and galvannealing.

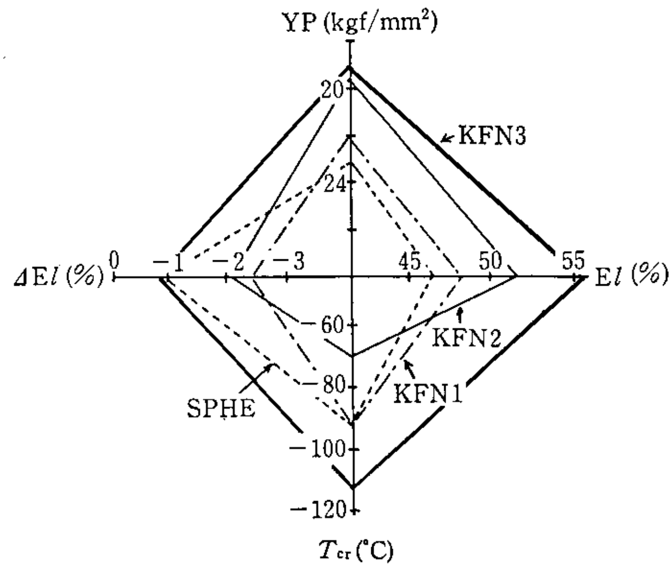


Fig. 9 Comparison of mechanical properties, YP, El, ΔEl and T_{cr}, of KFN3 with those of SPHE, KFN1 and KFN2 (3.2 mm thick)

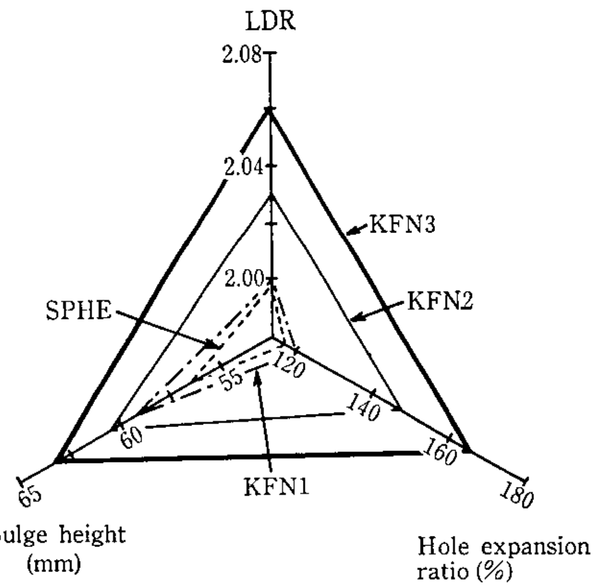


Fig. 10 Comparison of formability, limited drawing ratio (LDR), hydrobulge forming height and hole expansion ratio, of KFN3 with those of SPHE, KFN1 and KFN2 (3.2 mm thick)

6 Conclusions

The extradeep-drawing quality hot-rolled steel sheet KFN3 newly developed by Kawasaki Steel has been described. The manufacturing process and characteristics of KFN3 are summarized as follows:

(1) KFN3 is a Ti-bearing ultralow-carbon steel with a S content of 0.003% or less. This steel sheet is produced by low-temperature coiling after hot rolling.

(2) KFN3 provides excellent ductility of 55% or more at a thickness of 3.2 mm and is characterized by small planar anisotropy.

(3) By lowering the S content to 0.003% or less, it is possible to promote residual solute C even if Ti addition is conducted with an atomic ratio of effective Ti to C of 1.0 or more. Furthermore, Ti is effective in grain refining, giving KFN3 a high resistance to cold-work brittleness.

Kawasaki Steel has previously developed steel sheets such as KFN1 and KFN2 with excellent formability. Recently, the hot-rolled steel sheet KFN3 with the same formability as cold-rolled steel sheets has been developed. The authors believe that the excellent characteristics of KFN3 meet users' requirements, in particular for formability.

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